OpenBrush: An Open-Source Manual Toothbrush for Force and Motion Sensing

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Abstract

Toothbrushing force and duration are both critical to effective oral hygiene, yet manual toothbrushes, the most widely used globally, lack sensing capabilities for either. We present OpenBrush, a fully open-source[1], force-and-motion-aware manual toothbrush that integrates a load cell in the brush neck and an inertial measurement unit (IMU) in the handle. These sensors are connected to a Raspberry Pi Pico microcontroller for onboard processing and data logging. OpenBrush enables measurement of applied brushing force and motion dynamics, offering a low-cost platform for real-time feedback, brushing behavior research, and intelligent oral care applications. We describe the mechanical and electrical design of the system and evaluate its sensing fidelity through both controlled experiments and naturalistic brushing trials. Preliminary data demonstrate the system's ability to capture fine-grained variations in force and motion. By open-sourcing the hardware and software, OpenBrush aims to empower manual toothbrush users with accessible technology to improve brushing habits, while also contributing a reproducible foundation for the research community to advance studies in oral health sensing and human–toothbrush interaction.

CCS Concepts

• **Human-centered computing** → *Ubiquitous and mobile computing design and evaluation methods.*

Keywords

Toothbrushing monitoring; IMUs; Force Sensors

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[1]https://github.com/Qiangest/OpenBrush

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1 Introduction

Toothbrushing is one of the most fundamental daily activities for maintaining oral health. Effective brushing requires appropriate coverage across different regions of the mouth and the application of suitable brushing force [1]. Inadequate brushing may leave plaque behind, while excessive brushing can lead to enamel abrasion, gum recession, and long-term dental issues. Monitoring toothbrushing behaviors both in terms of location and applied pressure is therefore critical for encouraging healthy and effective brushing habits [1].

Smart electric toothbrushes have made notable progress in this regard. Many high-end models incorporate sensors that track brushing location and detect applied force. Some even provide real-time feedback using indicator lights or smartphone apps, warning users when excessive pressure is applied [2]. However, these devices remain expensive and are used by only a small fraction of the global population. In contrast, manual toothbrushes continue to dominate the market due to their affordability, simplicity, and accessibility [15]. Unfortunately, most manual toothbrush users lack any form of feedback on their brushing technique and are often unaware of harmful overbrushing behaviors.

In recent years, the research community has explored augmenting manual toothbrushing with sensing technologies. A number of works have focused on toothbrushing location tracking, using inertial sensors [5, 9, 16], audio signals [10, 17], or computer vision [6] to estimate which regions of the mouth are being brushed. *However, brushing force has received far less attention.* One major reason is the lack of a usable and flexible research platform for capturing ground-truth force during manual brushing. Some studies have attempted to address this by embedding force sensors directly into the bristle base or by modifying the brush head [3, 4, 11]. Yet these approaches are often intrusive, incompatible with different brush head types, and unsuitable for real-world use.

To address this gap, we present OpenBrush, a force-and-motion-aware manual toothbrush designed for both practical usability and research reproducibility. Our design integrates a load cell into the neck of a 3D-printed manual toothbrush, enabling indirect measurement of brushing force via strain deformation, without altering the brush head itself. This approach preserves normal brushing behavior while offering high sensitivity to applied pressure. Additionally, we embed an IMU into the toothbrush handle, supporting motion tracking and region recognition. All sensor signals are collected and

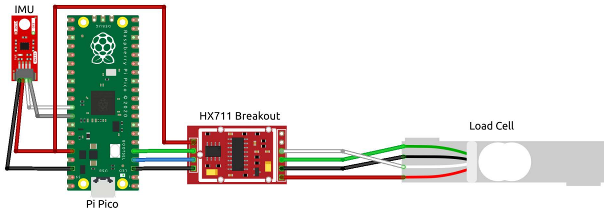
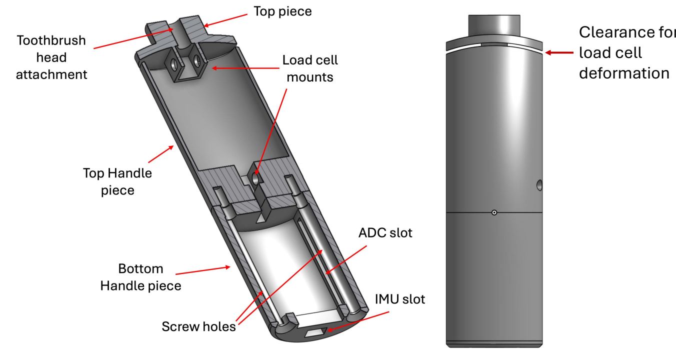


Figure 1: OpenBrush schematic.



(a) Inside **(b) Outside**

Figure 2: 3D-printed case.

logged via an onboard microcontroller. To summarize, our main contributions are as follows:

- We design and implement OpenBrush, a fully open-source, sensor-integrated manual toothbrush that can measure brushing force and motion without interfering with natural usage, enabling multimodal monitoring with a single device.
- We propose a load cell-based force sensing approach by embedding a load cell in the brush neck, offering a more practical and generalizable solution compared to bristle-mounted sensors.
- OpenBrush aims to bridge the gap between everyday manual toothbrush use and advanced brushing behavior monitoring, ultimately empowering both users and researchers to better understand and improve oral hygiene practices.

2 OpenBrush Design

2.1 Design Principle

To enable sensing of both brushing motion and applied force in a standard manual toothbrush form factor, we designed OpenBrush, a modular and open-source platform centered around a 3D-printed brush handle. The schematic is shown in Fig. 1. The design integrates two key sensing modalities: a load cell for capturing brushing force and an IMU for tracking motion and orientation. Both sensors are wired to an onboard microcontroller, which serves as the onboard controller for synchronized data acquisition and storage. This design preserves compatibility with off-the-shelf toothbrush heads and supports real-time, multi-modal sensing during natural brushing routines. The following sections detail each component of the system.

2.2 Hardware

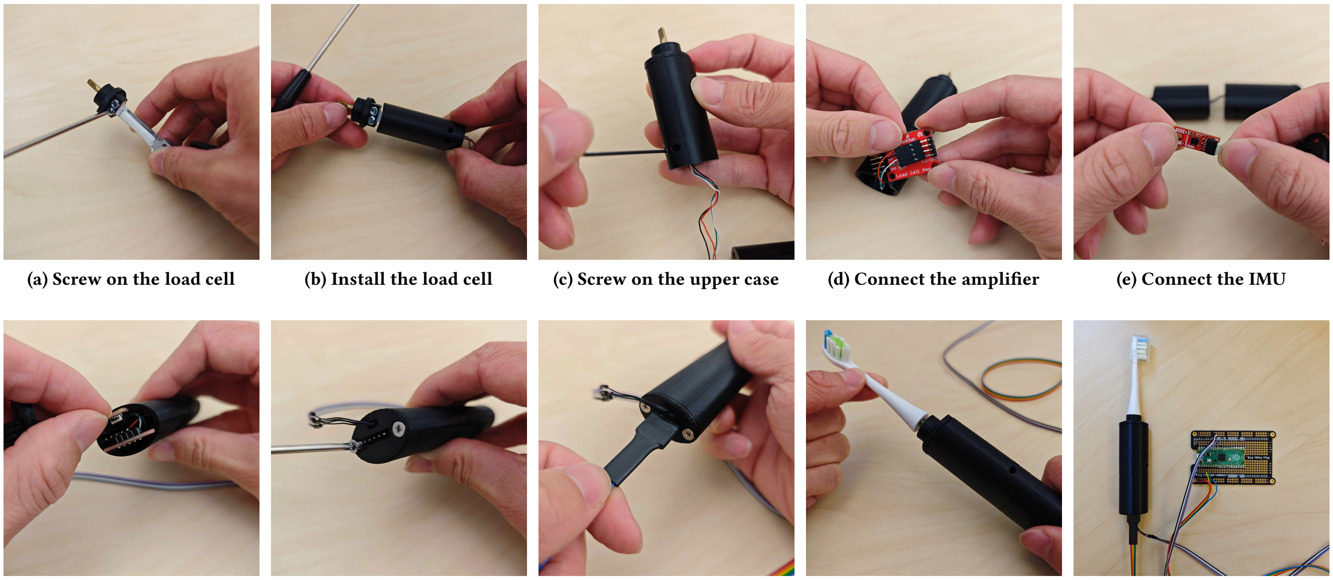
2.2.1 3D-Printed Brush Handle and IMU. As shown in Fig. 2, the body of OpenBrush is built around a custom-designed 3D-printed handle, which houses all internal components. Figure 2(a) shows the internal structure of the handle. The handle provides discrete compartments for securely mounting sensors and electronics, while maintaining a comfortable grip and familiar shape for users. The upper part of the handle is designed to fix the load cell securely, allowing it to deform under applied brushing force for accurate pressure sensing. In the lower part of the handle, we embed a SparkFun Micro 6DoF IMU [13]. This sensor offers both accelerometer and gyroscope readings and is capable of detecting hand motion, orientation, and brushing gestures. The IMU is positioned near the bottom of the handle to capture the full dynamics of the user's brushing movement with minimal interference from hand grip variability. We also design a dedicated slot for the load cell amplifier inside the lower handle.

2.2.2 Brush Head and Load Cell. To measure brushing force, we attach a Uxcell 500g Load Cell weighing sensor [8] to the neck of the toothbrush. The sensor is positioned to detect strain induced by force transmission during brushing. A short metal adapter rod is rigidly connected to the sensor and extends forward to allow the mounting of standard replaceable toothbrush heads. The analog output from the load cell is amplified by a SparkFun HX711 load cell amplifier [14], a widely used 24-bit ADC module embedded within the handle. This design ensures that the bristle contact force is transferred to the strain gauge through mechanical deformation, without requiring any modification to the brush head itself. Figure 2(b) illustrates the outer structure of the handle. To ensure accurate force measurements, we designed the case with a dedicated clearance around the load cell, allowing its mechanical deformation to proceed freely without interference from the surrounding structure.

2.2.3 Controller and Mechanical Assembly. As shown in Fig. 1, all sensor components are wired to a central Raspberry Pi Pico microcontroller [12], which is responsible for data sampling. The Pico is selected for its compact size, low power consumption, and sufficient GPIO/I^2C support to interface with both the IMU and HX711 amplifier. Figure 3 illustrates the step-by-step assembly of OpenBrush. The entire assembly, including the load cell, amplifier, and IMU is mounted within the 3D-printed frame with careful consideration of mechanical isolation and wire routing. The design ensures stable signal acquisition while allowing the device to be handheld and used in everyday brushing scenarios.

2.3 Software

2.3.1 Firmware. The firmware for OpenBrush is implemented using `CircuitPython` [7] for its ease of development, hardware abstraction, and cross-platform compatibility. Upon startup, the firmware initializes both the IMU and the load cell system. Specifically, we use the `LSM6DSV16X` driver to communicate with the inertial measurement unit over I^2C. The IMU operates with the following full-scale



(a) Screw on the load cell (b) Install the load cell (c) Screw on the upper case (d) Connect the amplifier (e) Connect the IMU

(f) Insert the amplifier and IMU (g) Screw on the lower case (h) Connect the data cable (i) Attach the brush head (j) Connect to the controller

Figure 3: Assembly steps of OpenBrush.

range accelerometer: ±2g and gyroscope: ±250°/s. These ranges are suitable for detecting subtle brushing motions. The HX711 load cell amplifier is connected via GPIO and is initialized with tare (zeroing) at startup to remove baseline offset due to sensor drift or mechanical preloading.

2.3.2 Data Collection. During the first-time setup, the user is prompted to perform a calibration of the load cell. After confirming that the toothbrush is unloaded (*i.e.*, held freely without applying any external force), the firmware records a tare value. The user is then instructed to apply a known weight, typically 100 grams, to the brush head, which allows the system to compute a scalar conversion factor between raw ADC readings and physical force in grams. After calibration, the system enters a real-time data acquisition loop that synchronously logs: {3-axis accelerometer data, 3-axis gyroscope data, Load cell output (in grams)}. These data streams are timestamped and printed to the serial output, enabling live monitoring and offline logging for analysis.

2.3.3 Data Calibration. Due to the non-negligible weight of the metal adapter and brush head, changes in the handle's orientation relative to gravity introduce systematic bias into the strain measurement. As shown in Fig. 4, the raw output of the load cell gradually changes as the brush is rotated along the x-axis. To address this, we implement a gravity-compensated calibration using the gyroscope and accelerometer readings. Specifically, we calculate the rotation angle of the brush from its upright reference pose using gyroscope integration, and estimate the gravitational torque component acting on the load cell at each orientation. We then subtract this orientation-induced offset from the raw load cell data to isolate the true dynamic force applied by the user. Fig. 4 shows that the impact of the brush head's self-weight has been eliminated, resulting in a calibrated force close to zero.

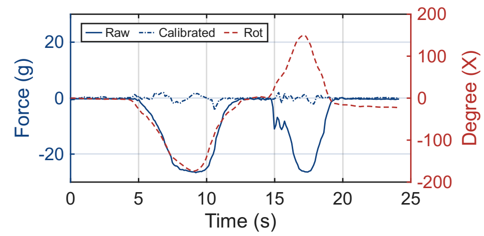


Figure 4: Data calibration.

3 Evaluation

To evaluate the sensing accuracy and usability of OpenBrush, we conducted both controlled and real-world experiments. Our evaluation focuses on two aspects: (1) the precision of the load cell in measuring known forces, and (2) the system's ability to capture realistic brushing force and motion data during actual toothbrushing sessions.

3.1 Static Weight Test

After performing scalar calibration, we validated the load cell measurements using standard calibration weights ranging from 50 g to 350 g. Each weight was applied directly to the brush head mounting point while the handle was held upright and fixed in position. We recorded the load cell output after compensating for orientation. As shown in Fig. 5, the results demonstrate a consistent response across all tested weights, with a mean absolute error (MAE) of 0.43 g and a standard deviation (Std) of 1.2 g . This confirms that OpenBrush can accurately measure static forces within the typical toothbrushing force range (50–400 g).

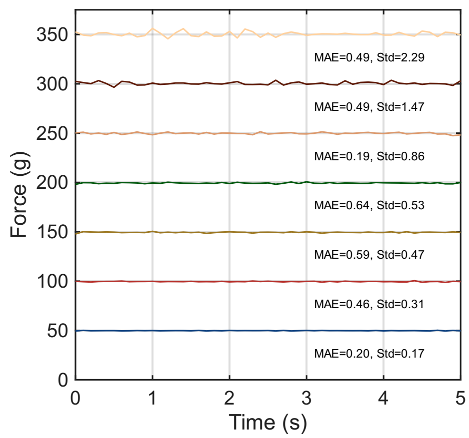


Figure 5: Static weight test.

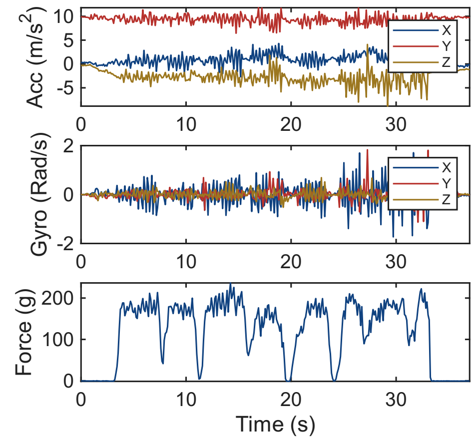


Figure 6: OpenBrush sensor signals.

For each tested weight, we report the corresponding MAE and standard deviation to assess accuracy and stability. Interestingly, while the MAE remains relatively consistent across different weights, we observe increasing variance at higher force levels. This is likely because the load cell exhibits better responsiveness and stability in the lower force range, which aligns with the typical force range in everyday brushing.

3.2 Toothbrushing Motion and Force

We further evaluated the system in real-world scenarios. Participants were asked to brush their teeth naturally while holding the OpenBrush in one hand. During each session, both the brushing force and IMU data were recorded in real time. The data acquisition was conducted at a fixed sampling rate of 20 Hz. As shown in Fig. 6, the system successfully captured a variety of brushing behaviors, including typical oscillatory motions and changes in applied force. We observed variations in both motion patterns and pressure levels, consistent with prior findings in toothbrushing behavior research. The synchronized IMU and force data will further enable analysis of brushing style, handedness, and coverage distribution in future work.

4 Conclusion

We presented OpenBrush, an open-source manual toothbrush platform that integrates a load cell and IMU to enable brushing force and motion sensing. Unlike prior work focusing mainly on brushing location, OpenBrush highlights the often-overlooked role of force in oral health. By providing an accurate, reproducible, and easy-to-use tool, we aim to support future research on brushing patterns and empower the broader community with a practical platform for studying and improving manual toothbrushing behavior. In the future, OpenBrush can serve as a foundation for research in real-time feedback systems, user habit modeling, multi-modal brushing behavior analysis, and even clinical studies on personalized oral care strategies.

Acknowledgments

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References

[1] 2024. 3 Tooth Brushing Techniques | Colgate®. https://www.colgate.com/en-us/oral-health/brushing-and-flossing/3-tooth-brushing-techniques-that-get-the-job-done. (Accessed on 05/01/2024).
[2] 2024. iO Series 10 Rechargeable Electric Toothbrush | Oral-B. https://oralb.com/en-us/products/electric-toothbrushes/io-series-10-rechargeable-electric-toothbrush-cosmic-black/. (Accessed on 05/01/2024).
[3] Md Akhtaruzzaman. 2019. Prototype of a force-sensitive smart toothbrush. In *Proc. EICT, 4th Int. Conf.*
[4] Md Akhtaruzzaman. 2021. Force-Sensitive Classic Toothbrush: System Analysis, Design, and Simulation. *Electrica* 21, 2 (2021).
[5] Sayma Akther, Nazir Saleheen, Mithun Saha, Vivek Shetty, and Santosh Kumar. 2021. mteeth: Identifying brushing teeth surfaces using wrist-worn inertial sensors. *Proceedings of the ACM on interactive, mobile, wearable and ubiquitous technologies* 5, 2 (2021), 1–25.
[6] Yu-Chen Chang, Jin-Ling Lo, Chao-Ju Huang, Nan-Yi Hsu, Hao-Hua Chu, Hsin-Yen Wang, Pei-Yu Chi, and Ya-Lin Hsieh. 2008. Playful toothbrush: ubicomp technology for teaching tooth brushing to kindergarten children. In *Proceedings of the SIGCHI conference on human factors in computing systems*. 363–372.
[7] CircuitPython. 2025. The easiest way to program microcontrollers. https://circuitpython.org/ [Online; accessed 2025-05-29].
[8] ebay. 2025. 500g Weighing Electronic Balance Wired Load Cell Weighing Sensor. https://www.ebay.co.uk/itm/382842518684 [Online; accessed 2025-05-29].
[9] Hua Huang and Shan Lin. 2016. Toothbrushing monitoring using wrist watch. In *Proceedings of the 14th ACM Conference on Embedded Network Sensor Systems CD-ROM*. 202–215.
[10] Joseph Korpela, Ryosuke Miyaji, Takuya Maekawa, Kazunori Nozaki, and Hiroo Tamagawa. 2015. Evaluating tooth brushing performance with smartphone sound data. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. 109–120.
[11] Haicui Li and Lei Jing. 2023. 3D Monitoring of Toothbrushing Regions and Force Using Multimodal Sensors and Unity. *IEEE Access* (2023).
[12] Raspberry Pi Ltd. [n. d.]. Buy a Raspberry Pi Pico – Raspberry Pi. https://www.raspberrypi.com/products/raspberry-pi-pico/ [Online; accessed 2025-05-29].
[13] SparkFun. 2025. SEN-21336 SparkFun | Mouser United Kingdom. https://www.mouser.co.uk/ProductDetail/SparkFun/SEN-21336?qs=VJzv269c%252BPYOh5zqmfn3Rg%3D%3D [Online; accessed 2025-05-29].
[14] SparkFun. 2025. SparkFun Load Cell Amplifier - HX711. https://www.sparkfun.com/sparkfun-load-cell-amplifier-hx711.html. [Online; accessed 2025-05-29].
[15] Statista. 2024. U.S.: usage of manual toothbrushes 2011-2024 | Statista. https://www.statista.com/statistics/287357/usage-of-manual-toothbrushes-in-the-us-trend/. (Accessed on 04/03/2024).
[16] Qiang Yang, Yang Liu, Jake Stuchbury-Wass, Kayla-Jade Butkow, Dong Ma, and Cecilia Mascolo. 2024. BrushBuds: Toothbrushing Tracking Using Earphone IMUs. In *Companion of the 2024 on ACM International Joint Conference on Pervasive and Ubiquitous Computing*. 655–660.
[17] Qiang Yang, Yang Liu, Jake Stuchbury-Wass, Kayla-Jade Butkow, Emeli Panariti, Dong Ma, and Cecilia Mascolo. 2025. SmarTeeth: Augmenting Manual Toothbrushing with In-ear Microphones. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. 1–19.